Thinned Charge Coupled Devices with Flat Focal Planes for UV Imaging

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Abstract

A versatile post-fabrication process to produce thinned, flat, back-illuminated CCDs is being developed at Jet Propulsion Laboratory's Microdevices Laboratory. This technique is compatible with many ultraviolet enhancement treatments and has been demonstrated with the delta doping process. The significance of this demonstration is that thinned, robust, and flat CCDs are produced without the use of epoxies or waxes using temperatures and materials that are compatible with standard CCD fabrication and delta doping processes.

In our approach, the CCD is attached by thermocompression bonding to a specially-designed silicon substrate using gold-gold diffusion bonding prior to thinning. CCDs with optically flat membranes (10-20 μm) were produced and the yield for this process is excellent. These flat CCDs have been successfully delta doped. We will discuss the process of producing thinned flat CCDs, their delta doping, and our results to date.

Introduction

Charge-coupled devices (CCDs) are the detectors of choice for many NASA applications. Back-illuminated CCDs potentially have the highest quantum efficiency in the ultraviolet and visible parts of the spectrum. However, they require removal of the silicon substrate (thinning) and a surface treatment of the backside of the CCD to allow detection of UV photons (accumulation or backside treatment).

Generally, back-illuminated CCDs require thinning of the device down to a thickness of only 10 to 20 μm which matches that of the silicon epilayer (a property of the original CCD design). A natural consequence of having such a thin structure laced with electronic circuitry is that it will wrinkle with a height variation of 30 to 50 μm. Astronomy applications dictate that the focal plane of the CCD be flat within fractions of a micron. Furthermore, this membrane is fragile and prone to fracture when subjected to repeated flexing which is inevitable in the temperature cycling of operational instruments.

To achieve a thinned, flat focal plane array, a rigid support could be attached to the CCD prior to the thinning process. Our concern in this development was that the method of attachment of the support substrate had to be compatible with the processing temperatures and ultrahigh vacuum requirements of delta doping.

A number of such UV-enhancement treatments have been demonstrated for back-illuminated CCDs [see for example: Janesick89, Lesser96, Hoenk92]. Our group at Jet Propulsion Laboratory's Microdevices Laboratory developed the delta doping process to address UV enhancement of CCDs in 1992. Delta-doped CCDs exhibit uniform and stable 100% internal quantum efficiency in the visible and ultraviolet regions of the spectrum without hysteresis. Initial developments of delta doping involved collaboration with EG&G Reticon for procurement of thinned scientific CCDs. However, as Reticon moved away from production of thinned scientific CCDs, and in the absence of other known compatible sources of thinned CCDs, we launched an effort to develop an in-house post-fabrication process for producing thinned CCDs with flat focal planes that can be delta doped. It should be noted that Professor M. Lesser's thinning process at University of Arizona [Lesser92] requires epoxy which is not compatible with delta doping, and only in the last year, SITe's proprietary thinning process has been demonstrated (at JPL) to be compatible with the delta doping process (see paper by P. Deelman in these proceedings). The advantages of our in-house thinning approach include versatility and compatibility with different CCD fabrication approaches and formats, working on both small and large quantities of devices, and compatibility with delta-doping.

Our group at the Microdevices Laboratory at JPL has developed a procedure for the production of flat, mirror-finished, thinned CCDs. This technique is universally compatible with UV enhancement approaches including the delta doping process. In this technique, prior to thinning of the CCD, gold-gold diffusion bonding is employed to attach a silicon substrate to the frontside of the CCD by thermocompression bonding.

In the following sections, we will describe a brief background of other thinning approaches, our procedure for producing thinned flat focal plane array CCDs, the quality and yield of our process, delta doping of these devices, and our preliminary results.

Procedure for Producing Flat Thinned CCDs

Our bonding and thinning development has benefited from previous and existing work in this field. A number of thinning approaches have been developed over the years at different companies and institutions. A summary and historical account of these approaches can be found in (for example) a paper by Winzenread et. al. (1994). The early thinning efforts resulted in free-standing membranes (see for example Tektronix in [Winzenread 94]). Then several groups (RCA [Savoye84], University of Arizona

[Lesser92], EG&G Reticon [Winzenread94], SAIC [Schaefer91]) were able to produce thinned membranes supported on rigid substrates. Some of these are no longer available or are not compatible with the requirements of delta doping. At SITe, a proprietary process attaches a ceramic support with conductive traces to the CCD. As mentioned in the introduction, delta doping has been demonstrated with this approach.

Bonding

To achieve a rigid and flat focal plane, gold-gold diffusion bonding [Guo87] is employed for attachment of a specially-designed silicon substrate to the CCD frontside prior to thinning. Because the existence of gold, even in dopant levels, in the CCD structure has detrimental effects on the CCD performance, precautionary measures have been taken to prevent diffusion of gold into the CCD structure. The silicon substrate is designed to cover the entire CCD and has pre-cut openings to enable wiring access to the CCD's bond pads (see figure 1). Trilayers of titanium, platinum, and gold are deposited on both the silicon substrate and the frontside of the CCD. The platinum layer provides a diffusion barrier between gold and silicon and the titanium layer improves the adhesion of the other metals to the protective oxide of the CCD. The thicknesses and evaporation rates of titanium and platinum have been set to reduce to a minimum acceptable level the exposure to x-rays generated by the electron beam heating of the metals.

Figure 1. A secondary electron micrograph of the silicon substrate used as structural support for the CCD prior to the thinning. As shown in the figure, pre-cut openings allow access to the bond pads for wiring purposes.

After placing the titanium and platinum layers a thick 10,000 Å layer of gold is applied by thermal evaporation. The result is a 20,000 Å layer of gold holding the CCD to a similarly treated silicon substrate in the thermocompression bonding. The trilayer is designed with this thickness in order to fill the valleys and voids that exist between the pixels in the field of a CCD. The CCD and the substrate are placed face to face such that the gold layers on each are in aligned, at 400°C, and under a load of approximately 1000 Nt/cm^2 for 30 minutes in vacuum. SEM analysis of a cross-section of this stack shows that the gold has flowed into the deep parts of the pixels as planned and no damage was done to the gate structure of the CCD. Scanning acoustic microscopy and cross-sectional

scanning was used to evaluate the bond integrity for several trials of thicnknesses and bonding parameters.

Thinning

Our backside thinning process begins with chemical-mechanical polishing of the backside of the CCD to achieve a mirror-smooth surface. This process is accomplished prior to bonding (either as an individual die or as an entire wafer) at Riotech in Arizona.

We employ frame thinning [Winzenread94] by leaving a thick area under the bondpads. Also prior to bonding, the region to be thinned is sharply defined on the backside by the application of a protective nitride layer using Plasma Enhanced Chemical Vapor Deposition (PECVD). This nitride layer blocks the etching action of our bulk material etchant KOH. There are nine die treated in a PECVD batch. Shadow masking is used to define the frame for nitride deposition which determines the area to be etched. A special alignment device was built to place the masks and hold the CCDs during the nitride deposition.

KOH Bulk Etch

The etchant we have selected for bulk material removal is hot KOH [Kung91]. This isotropic etchant has the benefit of retaining the mirror-smooth finish all through its silicon removal process. We have found it necessary to apply the hot KOH in a carefully controlled refluxer. The bath is maintained at 80°C and stirred continuously. The CCD/substrate assembly is protected by a fixture made of polypropylene. The fixture uses gaskets to seal the circuitry of the CCD from the KOH. The CCD is placed with its polished side exposed through an opening of the fixture. At several points during the KOH etch process the fixture is removed, rinsed, and dried in order to measure the depth of the etch. The exposure times are calculated to bring the depth of the etched well to within 20 μm of the device's epilayer.

To enable maximum flexibility, we have developed the approach to so that it may applied to any CCD (wafer or die) from any manufacturer. An aspect of this approach is that only the silicon under the active pixels is removed, leaving a thick border of silicon under the bond pads for wirebonding. This approach is also amenable to buttable CCD formats for mosaic structures. The thinning fixture is shown in figure 2. The fixture protects the CCD and defines the area to be thinned. The fixture is a four-piece design incorporating a base plate, top cap, compression plate, and a snorkel. Custom gaskets are used to seal the die in the fixture. The top plate, base cap, and snorkel material are polypropylene. There is a compression plate made of quartz that presses the CCD against the gasket. The top plate has a through-hole which allows the KOH to reach the CCD backside surface. A gasket with the same size opening is located around the hole and defines the thinning area in conjunction with the nitride frame described above. The

gasket material is DuPont Kal-Rez perfluoroelastomer which is able to withstand strong acids and bases. The assembled fixture is oriented so that the through-hole is facing up. The snorkel, added to the top plate, allows the air inside the fixture to expand and escape. A small o-ring at its base provides a fluid tight seal. The same design, with minor modifications, accommodates both individual die or full wafer thinning.

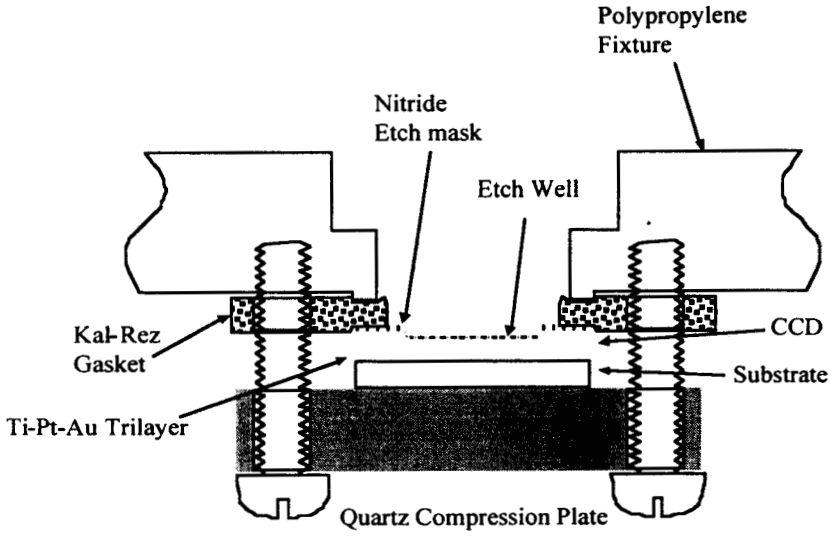

Figure 2 Schematic of polypropylene fixture for thinning of CCDs in a bath of hot KOH.

HNA Etches

The final approach to the epilayer is made by etching with solutions of hydrofluoric acid, nitric acid, and acetic acid (HNA) [Lesser92, Kovacs98]. HNA is used at this point because it has an etch rate that is strongly dependent on the silicon's resistivity. The etch rate of HNA therefore drops as the etching process encounters the epilayer interface just under the CCD electronics. The HNA removes about 1.5 μm per minute in the bulk silicon but that rate drops by nearly two orders of magnitude as the resistivity changes at the epilayer. The result is that the HNA can carefully remove all bulk silicon right up to the epilayer and not go far beyond that. The first solution of HNA is a classic 1:3:8 and is used to remove about 20 μm of bulk silicon. This etch is closely monitored for arrival at the epilayer. The arrival is indicated by change in the color, pattern and intensity of the activity at the solid liquid interface. A brief 60 second exposure to a second HNA solution (1:40:15) is used to remove a characteristic dark haze left by the first etch.

$KMnO_4$ Etch

The final etch step is quick exposure to a solution of $KMnO_4$ in hydroflouric acid [Lesser92]. This is a 90 second exposure that removes a characteristic faint white haze left by the HNA etching.

Delta-Doping of Thermocompressionally Bonded and Thinned CCDs

The ultimate test of a thinning and bonding procedure for producing flat, thinned back illuminated CCDs is their UV performance. For this purpose, we have applied the delta doping process the bonded and thinned CCDs.

Thinned CCDs are probe tested at die level for functionality. Functional CCDs are carefully cleaned by a multi-step solvent soaking and rinsing process [Hoenk92]. The thinned CCDs are individually soaked in beakers of hot xylene, Nophenol 922, and isopropyl alcohol (Nophenol 922 is a universal photoresist stripper produced by EKC Technology, Inc.). Then, they are rinsed with Transene 100 while mounted on a wafer spinner at 3000 rpm (Transene 100 is isopropyl alcohol with an added surfactant produced by Transene Company, Inc.). Following the solvent cleaning, UV/ozone plasma cleaning process is performed on the CCDs. Following this step, the oxide layer of the silicon surface (formed on the silicon surface as a result of the UV/ozone clean) is removed by a 5:1 solution of hydrofluoric acid in ethanol in a nitrogen glove box while the CCD is spinning at 3000 rpm. Then the CCDs are loaded in special fixtures and are passed directly into the ultra-high vacuum chamber of the molecular beam epitaxy system without any exposure to air. The delta doping process has been described in detail elsewhere [Hoenk92, Nikzad94a,b]. An epitaxial layer is grown on the back surface of a fully-processed, thinned CCD in the molecular beam epitaxy (MBE) system under ultra-high vacuum conditions (10^{-10} torr) using electron-beam evaporation of elemental silicon and thermal evaporation of elemental boron. The process requires heating the CCD to 450°C for a period of a few minutes. A 1 nm p^+ silicon layer is grown first, followed by an interruption of the silicon flux to deposit ~30% of a monolayer of boron atoms. A 1.5 nm capping layer of epitaxial silicon is then grown. After removal from the MBE system, ~1 nm of the silicon capping layer is converted to an oxide to protect the buried delta-doped layer.

The delta-doped CCDs are packaged and wire bonded at JPL. The package is machined with an opening on its underside to allow light to access the imaging surface of the CCD.

Results

The optical quality of the thinned CCDs is qualitatively illustrated in figure 3 where the reflected image of a JPL business card is shown on a fully-functional and

packaged delta-doped CCD. The reflection surface is the actual backside surface of the CCD's 20 μm thick membrane where UV photons are detected.

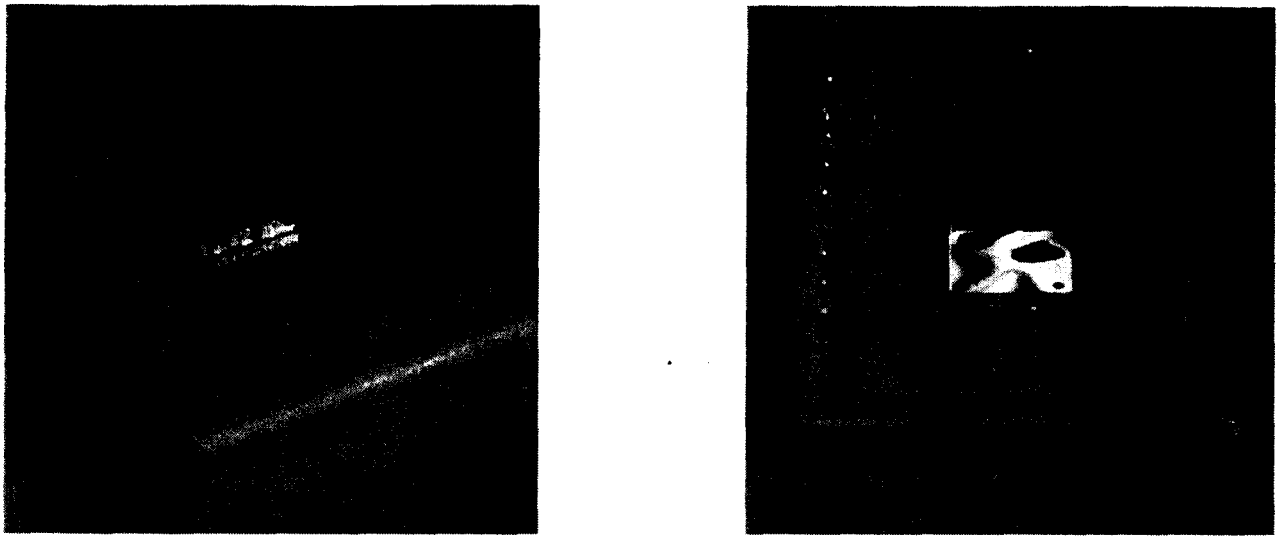

Figure 3. left) Picture of a thinned, structurally-supported (via thermocompression bonding) delta-doped CCD. The flat, mirror-finish membrane reflects the word "spectrometry". right) Photograph of the same type of CCD which was thinned without structural support, resulting in a free-standing membrane with a wrinkled surface.

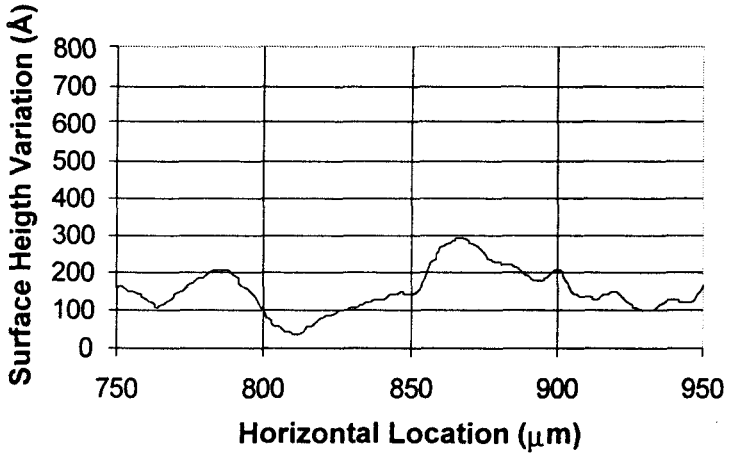

Figure 4 Local surface roughness in the etched well. The horizontal distance covered is 0.2 mm. This roughness is typical of the entire floor of the well.

Surface profilometry was used to quantify the optical flatness of the CCD at JPL and Surface Science Laboratories of Mountain View. The data In figure 4 show a 200 Å

peak-to-peak variation in the height of the etch surface. The data collected along a 200 μm span is typical of the entire etched surface. This degree of flatness is suitable for the demanding requirements of optics in astronomical instruments.

Several CCDs have been successfully bonded, thinned, and delta-doped using the techniques described above. Our preliminary results show enhancement of the quantum efficiency in the visible and the UV parts of the spectrum, however, these early measurements show lower than the expected values (~10-20% lower than theoretical limit). Efforts for further investigation is underway to explore the source of the reduction.

In conclusion we have established a method of producing flat, thinned, back illuminated CCDs. This process can be adapted for large CCDs and further investigation is underway for this extension.

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